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Clean and Sustainable Fusion Energy for the Future

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Abstract: Nuclear Fusion energy is one promising source of energy currently in the developmental stages with the potential to solve the world's energy crisis by providing a clean and almost limitless supply of energy for the entire planet. This meta-study analyses the heating systems, cooling systems, energy output, heating power input, plasma volume, economic impact, plasma temperature, plasma density, plasma confinement time and Lawson's Triple Product with respect to a variety of different nuclear fusion systems including the Wendelstein 7-X, the Helically Symmetric Stellarator Experiment, the ITER project, Joint European Torus, TFTR, IGNITOR and general information on tokamaks, stellarators as well as magnetic confinement of plasmas. Nuclear fusion is then more generally compared with four non-fusion energy sources, solar energy, wind energy, coal and hydroelectricity in terms of their overall economic impact, energy efficiency and environmental impact. Current global energy sources such as coal, oil and natural gas are briefly discussed with focus on their remaining global supply as well as their impact on the environment; this is contrasted with the remaining fuel supplies for nuclear fusion and fusion's environmental impact. The result of this meta-study was that we found that fusion power is a long term solution to the energy crisis and so more of a focus needs to be placed globally on working to expand the use of hydroelectric power.

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1. Introduction

1.1. Current and Future Energy Needs

Humanity is currently faced with an energy crisis brought on by rapid global population growth and the dependence of millions of people on electronic technology. The majority of the world's energy is currently derived from the burning of fossil fuels. Fossil fuels such as oil and coal are readily available and are relatively efficient and cost effective with respect to the amount of energy that they produce. They are, however, a limited and non-renewable resource meaning the world will eventually run out of its major source of energy.

The popularity of fossil-fuels has resulted in an enormous increase in the total quantity of CO_2 in the Earth's atmosphere. This increase in atmospheric CO_2 is the driving force behind global warming, thus it is evident that there is a serious need for the replacement of fossil-fuels with a clean and renewable alternative as the world's primary source of energy. Evidence regarding the increase in atmospheric CO_2 will be discussed in further detail in the body of this meta-study.

Nuclear fusion is a very promising source of renewable energy for the future. Fusion provides a large amount of energy for a very small amount of fuel when compared with that of coal, oil or nuclear fission[13]. This will be discussed in further detail in the body of this meta-study. An important advantage of fusion is the absence of direct radioactive reaction products, in contrast to fission, where radioactive waste is unavoidable due to the products of the energy releasing nuclear reaction are radioactive[13].

As well as fusion, there are several various other forms of energy production with the potential to provide clean and sustainable energy to the world long after fossil fuels are no longer an option. These other energy sources include solar, wind, hydro and biofuel as well as many others. Each of these non-fusion energy sources will be analysed further in this meta-study and then compared with each other as well as fusion energy as a whole with respect to the following parameters - economic viability, environmental impact and energy efficiency.

1.2. Focus of Meta-study

In 1955, John Lawson proposed a simple set of criteria which could be used to determine the overall efficiency of a nuclear fusion reactor. He determined that the energy yield for a fusion reactor depended on three quantities: plasma temperature (T), plasma density (n), and plasma confinement time (τ). This lead to what today's fusion scientists use - the triple product[7].

$$n\,\tau\,T$$

Increasing the value of the triple product is necessary for 'ignition' and thus for nuclear fusion to occur. As these three parameters are the base and most important parameters to calculate the efficiency of nuclear fusion reactors, they will be part of the focus of this meta-study. When comparing fusion power more generally with other non-fusion energy sources, the parameters analysed will be the overall energy efficiency of each type of energy production as well as the overall economic and environmental viability of each.

Overall, this meta-study will address the future of global energy production and the viability of fusion and other non-fusion energy sources.

1.3. Process of Nuclear Fusion

The least difficult fusion reaction to initiate on earth is that between the hydrogen isotopes D and T:

$$D + T \rightarrow 4\mathrm{He}\ (3.5\mathrm{MeV}) + \mathrm{n}\ (14.1\mathrm{MeV})$$

wherein which D stands for deuterium and T for tritium[13]. To produce sufficient fusion reactions, the temperature of the plasma has to be on the order of 100 to 200 million C for this reaction[13]. The reaction products are thus an α-particle (helium nucleus) and a very energetic neutron. Twenty percent of the energy is taken by the α-particles which are confined, owing to their charge, and deliver their energy to the background plasma. In this way they compensate for losses and might make the reaction self-sustaining. The kinetic energy of the fast neutrons will be converted into heat in a blanket and then into electricity using conventional technology (steam). Roughly a million times more energy is released from a fusion reaction than is by a normal chemical reaction; i.e. burning of fossil fuels[13].

The D-T fusion reaction is not the only possible reaction. Other types of reactions which work in theory are as follows:

$$\mathrm{D} + \mathrm{D} \rightarrow 3\mathrm{He}\ (0.82\mathrm{MeV}) + \mathrm{n}\ (2.45\mathrm{MeV})$$
$$\mathrm{D} + \mathrm{D} \rightarrow \mathrm{T}\ (1.01\mathrm{MeV}) + \mathrm{H}\ (3.02\mathrm{MeV})$$
$$\mathrm{D} + 3\mathrm{He} \rightarrow 4\mathrm{He}\ (3.6\mathrm{MeV}) + \mathrm{H}\ (14.7\mathrm{MeV})$$

A reactor based on the D+D reaction would remove the requirement for tritium as a reactant and would produce neutrons with lower energies than those produced in D-T reactions, these lower energies would enable the neutrons to be absorbed more easily into the blanket. A reactor based on the D+3He reaction would proceed very slowly and would produce very few neutrons. The prospects for these alternate fusion reactions are still mainly theoretical and so for that reason only the D-T reaction has immediate future prospects[13].

These reactions can occur in a variety of ways. The two main means by which fusion is achieved that is analysed in this meta-study are with the use of a tokamak and the use of a stellarator, both of which use the method of magnetic confinement of the plasma.[2]

Magnetic confinement fusion is one of two major confinement methods used to confine the fusion material. In this method, D-T fuel in the form of high temperature plasma is confined using magnetic fields. For D -T fuel, a temperature in the order of 10^8 K is required. A second requirement is that the product of fuel particle density *n* and confinement time r should be in the range of 10^{14}-10^{15} s/cm^3 . In magnetic confinement fusion reactors, r is approximately 1s and n is in the range of 10^{14} cm^{-3}.

Magnetic Confinement systems have attracted a lot of research based attention over the past years, and systems based on it are hence highly developed, efficient and promising. To achieve high efficiencies, particles must be prevented from colliding with reactor walls, as the collisions result in heat energy dissipation. Magnetic fields are ideal for confining plasma as the electrical charges on the separated particles (positive ions and electrons) mean that they adhere to the magnetic field lines. The most effective magnetic confinement systems are toroidal (doughnut shaped; i.e. the tokamak). In these systems, the magnetic field is curved around to form a closed loop, much like a reel of Copper wire wound around an Iron core. In order to ensure proper confinement, a perpendicular field component must be superimposed upon it. This results in a magnetic field with field lines that follow helical paths. These field lines confine and control the plasma. There are several types of toroidal magnetic confinement systems, namely Tokamaks and Stellarators. They are both discussed in detail below.

Approximately 450 fission power plants are in operation throughout the world, however, a successful commercial fusion power plant is yet to be made[7].

2. Methods

There was no restriction on the date of publication of the articles analysed. This enabled us to access articles published at any point in time before the writing of this meta-study which was necessary as the concepts and technologies surrounding fusion power have been developed gradually over more than 80 years. We thus needed access to both older and more recent articles so as to gain a broader understanding of the development of fusion science to the point at which it is today.

A variety of databases were utilised. The main database used to find articles was the UTS: Library Database as it gave access to a sufficient range of articles for the discussion of a variety of aspects of fusion power. To a lesser extent, articles were retrieved from other sources such as the reference lists of Wikipedia pages and Google Scholar. Information was not taken directly from Wikipedia itself as it is an unreliable source due to there being no strict regulation of the information presented there.

It was necessary to analyse several different aspects such as plasma confinement time, heating systems, energy input and the temperature conditions necessary for the plasma to be able to achieve fusion. Therefore it was necessary to collect different sources relating to each aspect of the fusion systems.

Since the range of parameters analysed and compared for each fusion system was intentionally limited to only those relating to Lawson's Triple Product as well as the overall cost and environmental impact of each system, only data relating to those factors was searched for. Information regarding other elements of each energy generation system were ignored as that information did not relate to the aforementioned parameters to be analysed and so therefore was considered to be irrelevant.

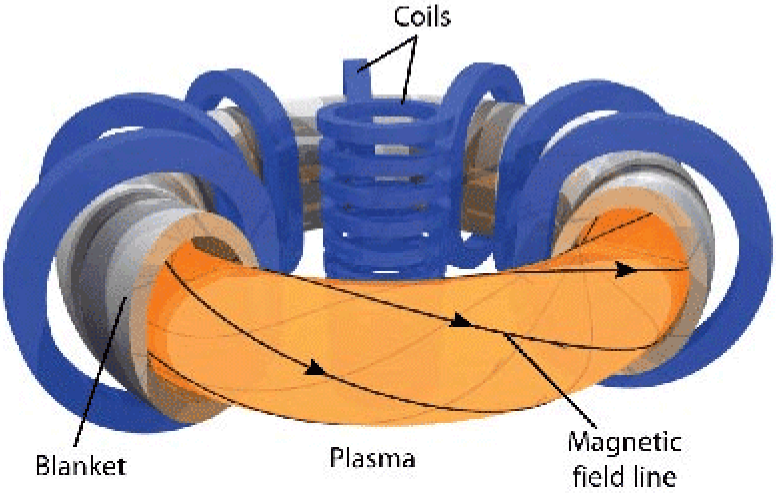
3. Results and Discussion

3.1. Tokamaks

Tokamaks are a form of magnetic-confinement fusion reactor in the shape of a torus developed in the Soviet Union in the 1950s. A tokamak is structured as a toroidal chamber surrounded by electromagnets which induce a current in suspended plasma. They have a cryogenic cooling system of usually liquid helium or nitrogen in order to shield the inside walls from high temperature neutrons released during the fusion process, as well as some form of heavy duty insulating shield, usually in the form of ceramic plating.

They operate by way of an induced magnetic field suspending a superhot plasma, often composed of deuterium and tritium (^{2}H and ^{3}H respectively), in a toroidal shape. Plasma used for fusion purposes is an extremely high temperature cloud of positively and negatively charged ions and electrons, with extremely high velocities as a result. The magnetic confinement is necessary in order to hold the ions in the centre of the torus, lest they risk rapidly losing their heat energy by colliding with the side of the tokamak, and also potentially heavily damage it as a result of their high temperatures.[29]

Figure 1: This image shows simplistically the geometric configuration of a tokamak, the direction of the plasma current within the vessel, the orientation and relative location of the coils and the location of the blanket[14].



Tokamaks exploit the fact that charged particles will experience a Lorentz force and follow the path of the poloidal field lines, moving from north to south in a circular motion, produced by an electromagnet. This holds the plasma in the centre of the torus, and with a slight "twist" to the field lines, can cause it to move through the torus and make the positive ions collide with the negative ions, due to them following opposite paths. While this occurs, some plasma will drift outwards towards the sides of the torus. Countering this, some plasma will also drift inwards to the centre, producing a macroscopic equilibrium and theoretically preventing the plasma from connecting with the side of the system.[29]

In order for a tokamak to run, it must first be heated to a temperature of over one hundred million degrees Celsius to maintain the plasma state. This is achieved through a variety of methods, and often more than a single one. Since plasma is an electrical conductor and there is already a current induced in a tokamak, Ohmic heating is generally made use of, where you can generate heat through the induced current via the resistance experienced. This can only heat it to twenty to thirty million degrees however, and so further heating methods are required.

A tokamak generates usable energy from the neutrons released when the colliding ions fuse and release energy and high temperature neutrons, which, due to their lack of electrical charge, move freely out of the plasma and collide with the walls of the system, making the aforementioned cooling systems necessary. The heat produced in the fusion reaction mostly contributes towards maintaining the high temperature the fusion reactor has to run at in order to maintain the plasma stream. Unfortunately, all current tokamaks, and even fusion devices in general, are unable to produce enough energy to even maintain their plasma state, let alone produce excess energy for servicing power needs.

3.1.1. TFTR

The Tokamak Fusion Test Reactor was an experimental tokamak at the Princeton Plasma Physics Laboratory which operated from 1982 to 1997. For its time, it was one of the most advanced tokamaks in existence, and made a number of significant contributions to their development:[31]

- It had the highest plasma temperature of its time at 510,000,000 degrees centigrade, more than five times the 100,000,000 required for fusion.

- It was the first tokamak to perform extensive experimentation with plasmas composed of a 50/50 deuterium/tritium fuel mix, the standard expected to be required for commercial fusion.
- It produced 10,700,000 watts of controlled power, enough to meet the needs of 3,000 homes.

In 1997, TFTR was retired, and many of its accomplishments were improved upon by JET. It nevertheless contributed considerably to the development of fusion power, and without its many advancements in the field, the progress on the currently existing JET or the currently worked upon ITER would no doubt be considerably slower.

3.1.2. JET

Currently, the Joint European Torus, or JET fusion reactor is the largest and most powerful operational tokamak in the world[15]. Its first plasma experiments began a year after its completion in 1983, and is also the only currently operational fusion reactor capable of using the D-T fuel mixture that is the be the main fuel mixture used in commercial fusion power stations in the future[15]. Today, its primary task is to prepare for the construction and operation of ITER, acting as a test bed for ITER technologies and plasma operating scenarios[15].

The cooling system for a fusion reactor is significant as it is the main factor limiting the pulse durations. Overheating of the JET coils is the main limiting factor for the duration of the JET discharges. JET is currently capable of a plasma discharge lasting 20 to 60 seconds depending on the strength of the magnetic field. During the plasma discharge, the temperature of the coils increases sharply. After the discharge their temperature slowly decreases to the level at which the next discharge is feasible[19].

3.1.3. ITER

The International Thermonuclear Experimental Reactor, or ITER, is an experimental tokamak fusion reactor currently in development in France intended to be completed by 2023[26], and have its first deuterium-tritium reactions by 2027. It is a collaborative project between several nations of the world, being contributed to by the European Union, India, Russia, China, South Korea, Japan and the United States of America.

ITER is expected to be the first tokamak, and indeed fusion reactor in general, to be able to produce more energy than was required for initiation, something which has not yet been achieved. This will mean it will be able to run itself on its energy alone, intending to produce over 500 megawatts of power. In spite of this, ITER is still only to be a testing ground for self-sustaining fusion reactors, and is only intended to be used in 500s intervals.

Since ITER is still not yet completed, all numbers produced for it are still just theory, and very subject to change as work on it progresses. To accommodate for this, the Joint European Torus, or JET, is a testing ground for ITER, which itself will be a testing ground for DEMO; the first fusion reactor to be used for the commercial production of energy.

3.1.4. DEMO

DEMOnstration Power Plant, or DEMO for short, is a proposed tokamak fusion generator which will be used to bridge the gap between ITER and commercial fusion reactors. As its development is dependent upon ITER’s success, there has been very little in the way of progress for its development, but there are some assumed baselines for it to function at:

1. DEMO is intended to produce at least four times the power of ITER, at 2GW.
2. It will do this on a continual basis, rather than in short bursts like tokamaks before it.
3. DEMO will produce electrical power, as all previous tokamaks have only produced heat which was later dissipated as steam.

Since DEMO is still in the conceptual stage there is much theoretical work yet to be done on it, and its eventual construction will only occur upon ITER's eventual completion and success. Like JET and ITER before it, DEMO will also act as a precursor to another tokamak fusion reactor, PROTO, which will be the first fusion reactor to produce power to be used by people commercially, though PROTO will likely not exist for at least another forty years.

3.1.5. IGNITOR

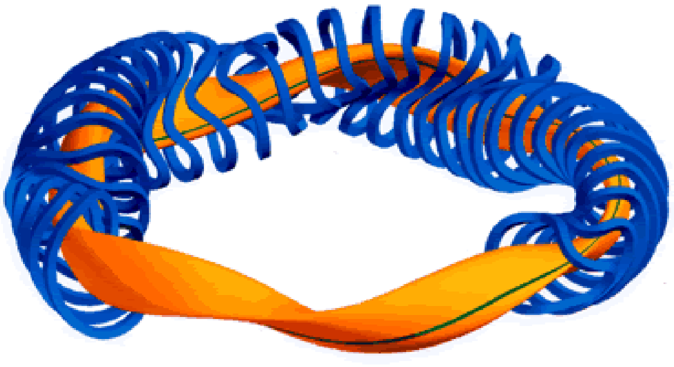
Ignitor is a high-field, high-current, high-density, low-β compact tokamak[37]. It was designed to be able to reach ignition at a relatively low temperature and high density (11KeV compared to the 17KeV required for the JET[37]) so that ignition by nuclear fusion reaction is achievable under controlled conditions.

Ignition in the IGNITOR is designed to be achieved through the combination of high toroidal and poloidal magnetic fields giving it a strong central pressure of less than 1.5MPa. In the case of the IGNITOR, in order to prevent the onset large oscillation within the central region, the poloidal magnetic fields need to be large and can get to about 30 times the poloidal magnetic fields reached at JET.

3.2. Stellarators

Similar to the tokamak, the stellarator is also based on a torus-shaped vessel, but relies completely upon meticulously designed coils to create the helically shaped magnetic field required to contain the plasma. This eliminates the necessity for a plasma current and thus removes the need for pulsed operation, making it an ideal concept for a fusion power plant[2].

Figure 2: This is a simple schematic diagram showing the geometric configuration of the plasma vessel (orange) and the magnetic coils (blue) of the Wendelstein 7-X stellarator[8].



The challenge lies in generating the helically shaped magnetic field. These design considerations, along with the costs of realising such intricate designs have made stellarators less common than tokamaks[2].

The stellarator system offers a distinct alternative to the main approaches to magnetic fusion power and has several potentially major advantages[1]. These advantages are listed below:

1. Plasma confinement during start-up and shutdown is aided by the presence of magnetic surfaces at all instances during this phase[1]
2. No need for Ohmic-current – permits steady-state operation[1].
3. Plasma operates in a “steady-state” after ignition[1].
4. Does not require expensive complicating auxiliary magnets for field shaping, position control coils and current drive[1].
5. Its coil configuration permits access to the device from all sides[1].
6. Since stellarators can operate free of induced toroidal current and do not suffer from major plasma disruptions, the major concern of an excessive energy dump on the first wall and plasma facing components can be eliminated[1].

The above mentions that the Stellarator design has the advantage of being able to operate in “steady-state” conditions. The term “Steady-state” simply indicates that, in a system, there is a variety of variables which remain unchanged over time. Steady-state operation is an intrinsic feature of stellarators since the vacuum magnetic field already provides plasma confinement[4].

The economic viability of stellarator reactors is mainly determined by the magnet system and the complexity of the blanket. These are the cost-driving components and for this reason any chance should be taken to operate the stellarator at low magnetic fields, even if this requires an increase in size[1].

3.2.1. Wendelstein 7-X

Currently, the advanced stellarator Wendelstein 7-X is in the assembly phase at the Max-Planck-Institut fur Plasmaphysik in Greifswald, Germany[5]. Its magnetic coils are twisted intricately to create the magnetic field required and they are superconducting in order to achieve the large magnetic fields that are required to confine the plasma[2]. Wendelstein 7-X (W7-X) will be the largest stellarator in the world. Its size will be sufficient to reach reactor relevant $nT\tau$ -values[3].

A very important aspect of the W7-X is the demonstration of high heating-power steady-state operation. To open the perspective for a stellarator reactor, however, steady-state operation has to be demonstrated in an integrated scenario at high heating power and densities relevant for a fusion reactor, simultaneously combined with a divertor providing reliable power particle exhaust[4]. In nuclear fusion, a divertor is simply a device which enables the removal of material from the fuel plasma whilst the reactor is in operation. This allows control over the build-up of fusion by-products in the fuel and removes impurities from the vessel. It will also test an optimised magnetic field for confining the plasma, which will be produced by a system of 50 non-planar and superconducting magnet coils, this being the technical core piece of the device[10].

The W7-X will be equipped with a set of neutron monitors in order to study the time behaviour of neutron emission generated during D-D plasma operation and neutral beam heating with Deuterium. The neutron rate represents a direct measure of the fusion rate and fusion energy and provides information on the ion temperature[6]. One of the monitors is located in the centre above the stellarator. The other five monitors are distributed around the torus[6].

The Wendelstein 7-X is not going to be operation until 2015[10], therefore it is impossible to know exactly what the energy output of this system will be.

3.2.2. HSX

The Helically Symmetric Experiment (HSX) is a quasi-helically symmetric (QHS) stellarator currently under construction at the Torsatron/Stellarator Laboratory of the University of Wisconsin-Madison. This device is unique in its magnetic design in that the magnetic field spectrum possesses only a single dominant (helical) component[16].

HSX is the only device in the world that has a magnetic field structure that has been termed Quasi-Helically Symmetric (QHS). Quasi-helically symmetric stellarators, to a good approximation, possess a direction of symmetry and are therefore topologically equivalent to a tokamak without plasma current[17].

Main goals of the HSX:

1. Demonstrate the feasibility of construction of a QHS device
2. Compare density and temperature profiles in this helically symmetric system to those for axisymmetric tokamaks and conventional stellarators
3. Investigate QHS effects on low collisionality (high-temperature) regime electron confinement
4. Examine how greatly-reduced neoclassical electron thermal conductivity compares to the experimentally measured electron thermal conductivity
5.

Main advantages of the HSX:

1. Intrinsically steady-state devices
2. No observed density limit
3. No required plasma current for confinement
4. No direct loss orbits
5. Good collisionless alpha particle confinement

The experimenters at Wisconsin University will determine whether two aspects of the transport, neoclassical electron thermal conductivity or anomalous thermal conductivity, benefit from the QHS configuration[17].

Tables 1. Tables contrasting the main parameters under analysis in this meta-study.

Parameter	**Wendelstein 7-X** [6,18,11]	**ITER**[24,25,28]	**JET**[19,12,20,21,22]	**TFTR**[31]
Heating System	*ECRH,1 *ICRH, *NBI	*NBI, *ICRH, *ECRH	*NBI, *ICRH, *LHCD	*NBI
Cooling System	Multi-layered Insulation, Liquid Nitrogen cooled brass panels	Cryostat to insulate the system with cooling water being pumped around it through openings as large as four metres in diameter	Pipe system of demineralised and deionised water pumped around the coils and heating devices	Vacuum and bellows cooling system, pumping cold air around the tokamak and pumping out hot air.
Energy Output	(Information not provided in literature)	Energy output *intended* to be 500MW by activation in 2023.	In 1997 - Produced 16.1MW of power. Is expected to run again in 2015 and due to the upgraded heating system is expected to produce more than 16.1MW of power.	In 1994 it produced 10.4MW of power. The reactor has since been decommissioned.
Heating Power Input	30MW	50MW	50MW	51MW
Plasma Volume	30m^3	840m^3	80m^3	(Information not provided in literature)
Cost	> €1billion	> €13,000,000,000	$100million per year	~ $240,000,000
Plasma Temperature (T)	100million°C	150,000,000°C	200million°C	510,000,000°C
Plasma Density (n)	3×10^{20}m^{-3}	1×10^{20}m^{-3}	0.9×10^{20}m^{-3}	(Information not provided in literature)
Plasma Confinement Time (τ)	0.15s	500s	0.1s - 1s	(Information not provided in literature)
Triple Product (nτT)(°Csm^3)	3x10^{28}	7.5x10^{30}	1.8x10^{28}	(Insufficient information for calculation)

Tables 1. Continued

Parameter	**IGNITOR**[37]	**DEMO**†	**HSX**[17]
Heating System	*ICRH, ohmic heating	N/A	*ECRH
Cooling System	(Information not provided in literature)	N/A	(Information not provided in literature)
Energy Output	19.2 MW	2GW	(Information not provided in literature)
Heating Power Input	(Information not provided in literature)	N/A	100kW
Plasma Volume	$10m^3$[37]	N/A	$0.44m^3$
Cost	(Information not provided in literature)	N/A	(Information not provided in literature)
Plasma Temperature (T)	100million°C	N/A	$\sim1.27x10^{-19}$ °C
Plasma Density (n)	$10^{21}m^{-3}$	N/A	$1\times10^{13}m^3$
Plasma Confinement Time (τ)	(Information not provided in literature)	Continuous	0.002s
Triple Product (nτT)(°Csm^{-3})	(Information not provided in literature)	(Information not provided in literature)	$2.54x10^{-9}$

*****Acronyms

NBI (Neutral Beam Injection) - NBI operates by injecting a high energy beam of neutral atoms into a fusion plasma, with the energy of these atoms transferred to it.

ECRH (Electron Cyclotron Resonance Heating) - ECRH works by superimposing a static magnetic field and a high-frequency electromagnetic field at the electron resonant frequency for a particular ionized plasma.

ICRH (Ion Cyclotron Resonance Heating) - ICRH works in much the same way as ECRH, however, it involves taking advantage of ions of elements rather than electrons.

LHCD (Lower Hybrid Current Drive) - Electrons in a plasma with a velocity slightly below that of the wave propagation can "surf" on the increasing electric potential and hence increase their velocity in the direction of the electromagnetic wave, creating a net electric current and maintaining heat.[39]

†Since DEMO is still in the planning stage, very little can be determined about its parameters beyond what is part of its mission statements.

From Tables 1 and 2 it is shown that the energy output of fusion reactors has been increasing over time, from 10.4MW at TFTR in 1994 to 16.1MW at JET in 1997 and then to the predicted 500MW at ITER once construction is complete. From this it can be predicted that the overall energy output of fusion systems will increase further as time progresses and as more research is done which should facilitate greater technological advancement.

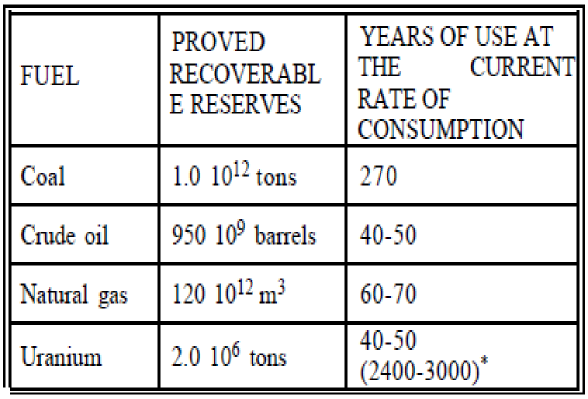
3.3. Non-fusion Energy Competitors

Nuclear fusion is not the only potential future energy source. Other renewable forms of energy which are in competition with nuclear fusion include solar power, wind power, hydroelectric power and coal. These energy sources compete with fusion in terms of their economic viability, energy efficiency and impact on the environment.

3.3.1. The Need for Renewables

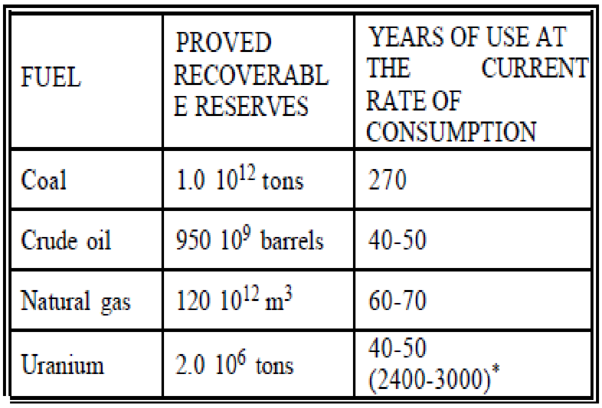
As shown by Table 3 below, 88% of the world total energy supply comes from coal, crude oil and natural gas. Table 2 shows, however, that each of these three energy sources has only 270, 40-50 and 60-70 years respectively before they are completely used up and unavailable to the world. This presents a serious problem for future generation as almost 90% of the world's energy supply will be gone, thus making it a necessity to look for alternative and more sustainable energy sources, fusion being one of those. Coupling this with the expected global population increase, global energy consumption rates will increase thus decreasing the expected remaining years available stated for coal, crude oil and natural gas[13].

Table 3 - The number of years worth of energy supply remaining for the four most dominant forms of energy supply for the world (as of 2004)[13].



FUEL	PROVED RECOVERABLE RESERVES	YEARS OF USE AT THE CURRENT RATE OF CONSUMPTION
Coal	1.0 10^{12} tons	270
Crude oil	950 10^{9} barrels	40-50
Natural gas	120 10^{12} m^3	60-70
Uranium	2.0 10^{6} tons	40-50 (2400-3000)*

Table 4 - The percentage contribution of different energy sources to the total world's energy production (as of 2004)[13].



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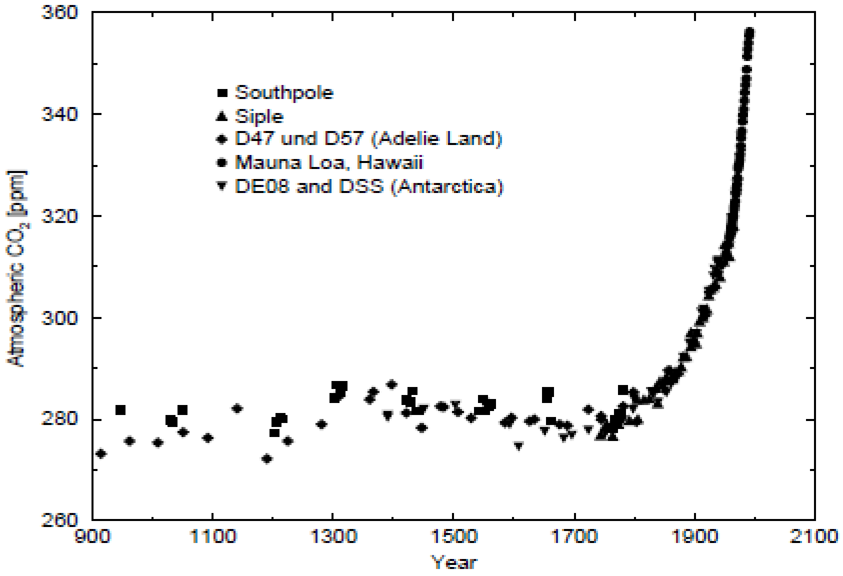
**If breeder technology is employed*

The other important reason for the urgent need to replace fossil fuels (coal, oil and natural gas) with a clean and renewable energy source such as fusion is the negative effects that carbon emissions have on the atmosphere. Graph 1 above displays evidence that carbon emission increases in the atmosphere are certainly due to human activities such as fossil fuel burning; the beginning of the exponential increase in atmospheric CO_2 is aligned almost exactly with the start of the Industrial Revolution (approx. 1760)[13].

Graph 1 - Graph showing rapid increase in atmospheric CO_2 content since industrialisation around the world[13].



3.3.2. Coal

While coal is not a renewable resource, it is one of the three substances used to produce energy that is categorized as fossil fuel and is the most abundant of the three, making it highly relevant. To produce electricity, coal is is first pulverised into a fine powder to increase its surface area leading to an increase in its combustibility. This powder is then combusted and the thermal energy produced is used to heat water and drive a steam turbine to generate electricity after which the steam is then condensed and recycled into a boiler drum where it is mixed with treaded water and reused to generate more electricity[32].

As addressed above, the production of energy through the burning of coal is known to have a negative impact on the environment as it emits CO_2 into the atmosphere. However, research is currently under progress to find ways to reduce the emission. Post combustion capture (PCC) is a method which is already widely used in the petrochemical industries to reduce the carbon emission and is done by absorbing the CO_2 into a liquid absorber such as amine before the flue gases of a power station is released into the atmosphere. The captured CO_2 is then liquefied and transported so that it can be safely stored in an underground strata[38].

3.3.3. Solar Power

Solar power works by harnessing the electromagnetic radiation which comes from the sun with the use of photovoltaic cells[23]. Photovoltaic cells are made of a semiconductor materials, usually silicon. Photovoltaic cells exploit the photoelectric effect which says that when a photon interacts with an atom an electron is released which can then be used to produce electricity[23]. They are, however, costly to produce and for that reason are not yet commercially viable for producing large amounts of energy as would be required to power millions of homes and businesses around the world[23].

The following table shows the increase of solar cell efficiency between 2005 and 2012:

Table 5[35] **-** Energy generation achieved for solar.

Year	Energy (TWh)	% of Total
2005	3.7	0.02
2006	5.0	0.03
2007	6.7	0.03
2008	11.2	0.06
2009	19.1	0.09
2010	30.4	0.14
2011	58.7	0.27
2012	93.0	0.41

Further information regarding the total cost, energy efficiency and environmental impact of solar power will be presented alongside fusion power and the other non-fusion energy sources discussed in this paper in a table below.

3.3.3.1. Nellis Air Force Base Solar Power System

The Nellis Air Force Bases solar power system is North America's largest solar photovoltaic power plant. It took 26 weeks to construct and was completed in 2007. It covers 566,560m^2 and provides the base with 14.2MW of power and an annual power output of 30,100,000 kWh. The solar power system will reduce CO^2 emissions by 24,000 tonnes annually, equivalent to planting 260,000 trees or removing 185,000 cars from the roadways.[36]

The system cost approximately $100million to construct, however, it is expected to save the Nellis Air Force Base $1million per year on the cost of energy. This solar power system uses the SunPower T20 Tracker technology which enables the solar panels to reorient themselves so as that they are directly aligned with the sun at all times, thus maximising their energy output.[36]

3.3.4. Wind Power

Wind power is a renewable source of power and is obtained by the conversion of the kinetic energy of wind into electrical energy. Among the other renewable sources like solar, hydroelectric and geothermal, to name a few, wind power generation has seen the fastest growth rate over the recent years. The reason for this is, according to Shojaeian and Akrami, wind power has been recognised as the most successful renewable energy source with the most untapped potential. The need for renewable energy has risen due to the resource limitations of the conventional energy sources mentioned above, as well as the emission problems caused by them.

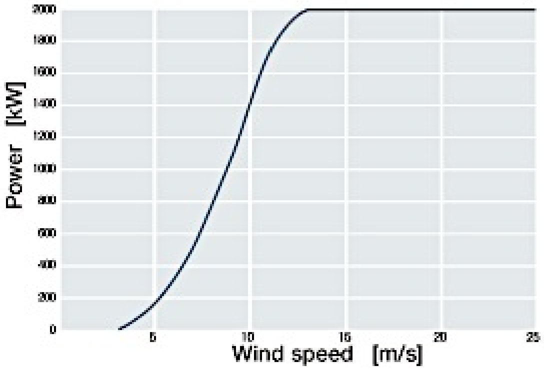
Wind power can be generated by converting the kinetic energy possessed by wind by virtue of its motion, into usable electrical energy. Wind Turbines are the core structures in Wind Power Generation systems, and can be classified into:

i. Horizontal Axis Wind Turbines (HAWT)
ii. Vertical Axis Wind Turbines (VAWT)

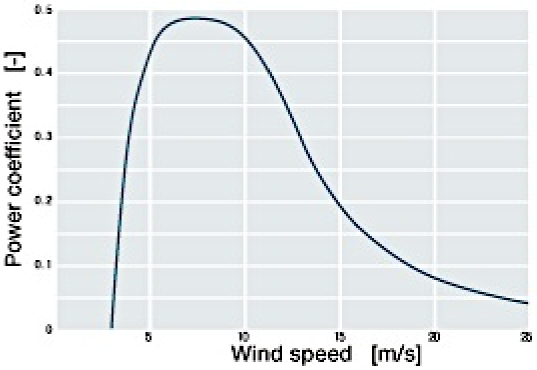
A system that uses HAWTs is detailed below.

3.3.4.1. Kamisu DAICHII Offshore Wind Farm

The *Kamisu DAIICHI Offshore Wind Farm* is located in the Minamihama, Kamisu, Ibaraki Prefecture in Japan. It consists of seven 2000kWh HAWTs and commenced operation in March 2010. Each turbine has a blade diameter of 80m. A graph showing the variation of power produced with wind velocity is given below:



As seen above, the Power generated rises at a constant rate between wind velocities of 3ms^{-1} to 12.5ms^{-1}. It then caps off at a maximum power of 2000kWh at wind velocities of 12.5ms^{-1} and higher. A graph comparing the variation of the power coefficient with wind velocity is given below.



The basic underlying principle behind wind power generation is electromagnetic induction. It can be summarized briefly as follows:

When wind passes through a turbine, it causes its blades to rotate. This rotation of the turbine blades are caused by the differential air pressure between the front and rear sides of the turbine. When the turbines rotate, it causes rotation of the central shaft connected to them via a set of gears. The rotation of the shaft within the generator causes a variation in the magnetic field associated with the generator coil, which in turn produces electricity. The biggest advantage of harnessing wind energy is that its basic requirement, wind, is a virtually inexhaustible resource. Its main advantages and drawbacks are summarised below:

Advantages:

- Wind energy is virtually inexhaustible
- Environment friendly. Causes no emissions
- Requires no combustion of fossil fuels. Hence highly sustainable

- Low land area usage. Wind turbines can be placed in city areas upon high rise buildings

Drawbacks:

- High Initial setup costs of $1.3-2.2 Million per MW of nameplate capacity.
- HAWT’s in operation are generally extremely noisy
- VAWT’s produce less noise but have a much lower average efficiency
- Wind sites are generally located in remote areas. Large lengths of transmission lines are required to connect wind sites to cities

3.3.5. Hydroelectricity

Hydroelectricity is power produced through harnessing the force of water falling or flowing due to gravity. It is the most widely used form of renewable energy in the world, accounting for more than 16% of the all energy produced in 2010 with over 3,400 terawatt-hours. It is additionally one of the cheaper forms of renewable energy, making it highly competitive with traditional forms of power generation, namely coal.[27]

Hydroelectricity is not without its shortfalls however, with most of them having considerable impact on the environment. While it may have one of the lowest greenhouse gas impacts of any form of electricity generation, for people to harness the forces of nature required to produce hydroelectricity, large river systems often need to be dammed, which can have dramatic impact on local ecosystems, and occasionally reservoirs will need to be produced, which can cause massive land loss and further damage to ecosystems.[30]

3.3.5.1. Hoover Dam

Hoover Dam is a hydroelectric power plant operating on the border of the states of Arizona and Nevada in the United States of America, taking advantage of the Colorado River. It was built in the years from 1931 to 1936, generates around four billion kilowatt-hours to serve the California, Nevada and Arizona regions, and was at one point in time the largest hydroelectric dam in the world.[33]

Hoover Dam operates by way of seventeen hydraulic turbines fed through penstocks from the Lake Mead reservoir. The turbines have a combined rating of 2,991,000 horsepower, which feed power produced from their rotations to generators with a combined capacity of 2,074,000 kilowatts.[33]

Table 6 - Table contrasting data relating to cost, energy efficiency and environmental impact of fusion with four non-fusion competing energy sources.

	Fusion	Solar	Wind	Hydroelectric	Coal

Cost (Short Term)	$100million - $20trillion	$1700-$2500 per Kw of installed photovoltaic (PV) panels (installed capacity)[34].	$1.3-2.2 Million per MW of nameplate capacity. Small scale turbines (under 100kW) cost roughly $3000-8000 per kW	High initial cost in the tens to hundreds of millions to build the dam and generator, as often it will cause significant damage to the local environment which must be mitigated.	$0.00798/Kwh
Cost (Long Term)	Almost free due to self-sustaining process	Almost free	Almost free as initial costs are overcome in a short period of time	Highly automated leading to low long term cost for producing power.	Coal supplies continue to dwindle as it is a non-renewable resource, thus there may not be coal available in the long term
Energy Efficiency	No exact efficiency value due to large number of different reactors. No fusion reactor is yet energetically commercially viable.	Best achieved efficiency of a photovoltaic cell to date has an efficiency of 41%[35]	Maximum theoretical efficiency achievable is 59%. HAWT have an average efficiecncy of ~35%	Modern hydroelectric plants have an efficiency of around 90%, which is very high compared to other contemporary forms of energy generation.	World average of about 31%
Environmental Impact	No negative impact other than land use	No negative impact other than land use	No negative environmental impact. Large wind farms however produce a considerable amount of noise.	Hydroelectricity produces the smallest amount of greenhouse gases of any power source, but also often causes large land loss due to dams and reservoirs.	Burning of coal to produce power is a main contributors to the release of CO_2 to the atmosphere. However, methods of damping the CO_2 emissions such as the PCC has been undertaken

Hoover Dam’s initial cost back in 1931 was approximately $50,000,000, but accounting for inflation this translates into a price point more than ten times that, pushing it towards nearly $700,000,000. However, in light of how automated and how little maintenance beyond occasionally upgrading the technology operating within it, the amount of power generated by it far offsets the initial high price.

4. Conclusions

From this study we have found that energy produced from nuclear fusion can potentially be a major source of power for humanity and may hold the key to solving future energy crises. However, it is also apparent that it is not a solution which will be achieved in the short term, and that in the meantime we will need to find another major power source - with the first commercial fusion power generator slated for post-2050 at the earliest, and with the setbacks experienced in the ones being developed simply to test the theory behind it, it would be unwise to put all our eggs in one basket.

Graph 1 shows that CO_2 content in the atmosphere is increasing at an alarming rate, therefore it is necessary to switch to a non-CO_2 form of energy, whether that be fusion or not. Significant progress has been made to improve the efficiency of photovoltaic technology, however, the efficiency of solar power doesn’t yet match that of hydroelectric power. For this reason, work should be done to improve the cost effectiveness of hydroelectric power so that it might be more easily replace carbon based fuels as the world’s main source of energy. Its high efficiency, renewable nature, and low greenhouse emissions compared to other power sources make it well suited for the task. Its high initial price may be a stumbling block for its possibility as an interval power source, but the relative lack of need for maintenance means generators utilising it need not be shut down once commercial fusion is achieved. One way of decreasing the cost of constructing a hydroelectric power station might be to find alternate, less expensive construction materials.

From analysis of the above fusion systems and from Table 1 and Table 2 it is evident that there is a significant amount of work being done to advance nuclear fusion technology. Most of the work is being focused around tokamak technology as they are simpler to assemble than stellarators. Stellarator technology has its advantages over tokamak technology, however. As shown by the HSX system, stellarators eliminate the requirement of a plasma current, there is no density limit for the plasmas and the fusion process is intrinsically steady-state for stellarator fusion. This indicates that, despite the convenience of not having to construct a complicated stellarator plasma vessel, the benefits of going with the stellarator model far outweigh the costs of producing it.

Ultimately, global demand for energy is going to continue to rise and the availability of current energy production fuels is going to decrease. Fusion is not going to be an immediate solution to the energy problem and so for that reason investments need to be made to improve and expand hydroelectric power generation technology immediately. In the long term, however, once fusion becomes a guaranteed option for large scale commercial energy production, fusion power should be adopted worldwide and if done so will provide the world with limitless clean energy billions of years into the future.

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